Motion-Induced Signal Loss in In Vivo Cardiac Diffusion-Weighted Imaging

Stoeck, Christian T ; Scott, Andrew D ; Ferreira, Pedro F ; Tunnicliffe, Elizabeth M ; Teh, Irvin ; Nielles-Vallespin, Sonia ; Moulin, Kevin ; Sosnovik, David E ; Viallon, Magalie ; Croisille, Pierre ; Kozerke, Sebastian ; Firmin, David N ; Ennis, Daniel B ; Schneider, Jurgen E

DOI: https://doi.org/10.1002/jmri.26767

HHS Public Access

Author manuscript

J Magn Reson Imaging. Author manuscript; available in PMC 2020 January 01.

Published in final edited form as:

J Magn Reson Imaging. 2020 January ; 51(1): 319–320. doi:10.1002/jmri.26767.

Motion-Induced Signal Loss in In Vivo Cardiac Diffusion-Weighted Imaging

Christian T. Stoeck[1], **Andrew D. Scott**[2,3], **Pedro F. Ferreira**[2,3], **Elizabeth M. Tunnicliffe**[4,5], **Irvin Teh**[6], **Sonia Nielles-Vallespin**[2,3], **Kevin Moulin**[7], **David E. Sosnovik**[8,9], **Magalie Viallon**[10,11], **Pierre Croisille**[10,11], **Sebastian Kozerke**[1], **David N. Firmin**[2,3], **Daniel B. Ennis**[7], **Jurgen E. Schneider**[6,12]

[1]Institute for Biomedical Engineering, University and ETH, Zurich, Switzerland [2]Cardiovascular Magnetic Resonance Unit, Royal Brompton Hospital, London, UK [3]National Heart and Lung Institute, Imperial College London, London, UK [4]University of Oxford Centre for Clinical Magnetic Resonance Research (OCMR), Radcliffe Department of Medicine, University of Oxford, Oxford, UK [5]NIHR Oxford Biomedical Research Centre, University of Oxford, Oxford, UK [6]Leeds Institute of Cardiovascular & Metabolic Medicine, University of Leeds, Leeds, UK [7]Department of Radiology, Stanford University, Stanford, California, USA [8]Cardiology Division, Massachusetts General Hospital, Harvard Medical School, Boston, Massachusetts, USA [9]Martinos Center for Biomedical Imaging, Massachusetts General Hospital, Harvard Medical School, Boston, Massachusetts, USA [10]Department of Radiology, University Hospital of Saint-Etienne, Saint-Etienne, France [11]CREATIS UMR CNRS5220 INSERM U1206, University of Lyon, Lyon, France [12]Division of Cardiovascular Medicine, Radcliffe Department of Medicine, University of Oxford, Oxford, UK

To the Editor:

In vivo cardiac diffusion-weighted imaging (DWI) has experienced a renaissance over the past several years. A key to its revival has been advances in magnetic resonance imaging (MRI) hardware technology and pulse sequences, including the continuous development of cardiac motion compensation strategies. Although none of these methods are currently available as commercial products, exciting pilot clinical studies hint that this method may become a new cardiovascular magnetic resonance (CMR) clinical tool in the near future.

The choice of imaging sequence and imaging parameters inevitably affects the measured diffusion indices.[1–3] However, the self-diffusivity of free water (2.92×10^{-3}mm^2/s at 35°C),[4] which is independent of the measurement sequence, provides a temperature-dependent physical upper limit for in vivo water diffusion. In soft tissues, microstructural diffusive barriers result in a reduced measured diffusivity. By using monopolar/motion-compensated gradient waveforms, measured diffusivities as low as $0.94–1.52 \times 10^{-3}$mm^2/s /$1.26–1.66 \times 10^{-3}$mm^2/s have been reported in blood at 37°C.[5]

In the 2013 article by Laissy et al,[6] 2017 article by Mou et al,[7] the 2018 article by Xiang et al,[8] and the 2018 ISMRM conference proceeding by Lan et al,[9] diffusivities of $6.32–8.95 \times 10^{-3}$mm^2/s,$3.04–3.38 \times 10^{-3}$mm^2/s, $1.7–3.5 \times 10^{-3}$mm^2/s and $3.77–3.84 \times 10^{-3}$mm^2/s,

respectively, have been reported for myocardium, which clearly exceed the upper limit defined by free water diffusion, and hence cannot be interpreted as measures of self-diffusion in cardiac tissue. We note that none of these studies report using any method to compensate for bulk motion and strain of the myocardium during diffusion encoding. Conventional DWI with spin-echo echo planar imaging (EPI) (even with ECG-gating) is artifact-prone and known to be ineffective in addressing the types and ranges of motion encountered in the in vivo heart, resulting in dephasing of the spins and apparent signal attenuation.

Mou et al[7] realized the large discrepancy with previously reported values and speculated that the excessively high diffusivities are related to the absence of parallel imaging, differences between SE and STEAM imaging, field strength, and even differences in ethnicity. While all these attributes may have an effect on the measurement results, the authors failed to identify the more obvious contribution of motion-induced signal attenuation, despite the hint in the study results: Mou et al[7] provide a clear correlation of their success rate of diastolic imaging to the subject's heart rate (the higher the heart rate the shorter the diastolic quiescent period and hence the lower the success rate). Furthermore, the authors report that at b-values above 300 s/mm^2 "remarkable signal loss of the myocardium or even an absent myocardium" was found. A b-value of 300 s/mm^2 is not considered excessively high and other studies have used larger b-values without suffering from signal loss (eg, Scott et al[10]: b_{max} = 750 s/mm^2 for STEAM or von Deuster et al[1]: b_{max} = 450 s/mm^2 for SE).

Diffusion metrics such as the apparent diffusion coefficient and the mean diffusivity have the potential to become clinically relevant biomarkers and methodological improvements continue to develop. The Society for Cardiovascular Magnetic Resonance Cardiac Diffusion Special Interest Group (https://scmr.org/members/group.aspx?code=Diffusion) is a potential resource for investigators interested in this topic. As the field advances, it is imperative and our collective responsibility to limit methodological inaccuracies, to correctly ascribe MRI signal changes to the correct underlying mechanism, and to mitigate misleading interpretations.

References

1. von Deuster C, Stoeck CT, Genet M, Atkinson D, Kozerke S. Spin echo versus stimulated echo diffusion tensor imaging of the in vivo human heart. Magn Reson Med 2016;76:862–872. [PubMed: 26445426]
2. Scott AD, Nielles-Vallespin S, Ferreira PF, et al. An in-vivo comparison of stimulated-echo and motion compensated spin-echo sequences for 3 T diffusion tensor cardiovascular magnetic resonance at multiple cardiac phases. J Cardiovasc Magn Reson 2018;20:1–15. [PubMed: 29298692]
3. Kiselev VG. Fundamentals of diffusion MRI physics. NMR Biomed 2017; 30:1–18.
4. Mills R Self-diffusion in normal and heavy water in the range 1–45.deg. J Phys Chem 1973;77:685–688.
5. Funck C, Laun FB, Wetscherek A. Characterization of the diffusion coefficient of blood. Magn Reson Med 2018;79:2752–2758. [PubMed: 28940621]
6. Laissy JP, Gaxotte V, Ironde-Laissy E, et al. Cardiac diffusion-weighted MR imaging in recent, subacute, and chronic myocardial infarction: A pilot study. J Magn Reson Imaging 2013;38: 1377–1387. [PubMed: 23564654]

7. Mou A, Zhang C, Li M, et al. Evaluation of myocardial microcirculation using intravoxel incoherent motion imaging. J Magn Reson Imaging 2017;46:1818–1828. [PubMed: 28306208]
8. Xiang S, Zhang X, Yang S, et al. STROBE — A preliminary investigation of IVIM-DWI in cardiac imaging. Medicine 2018;97.
9. Ian LS, Xin L, Yong ILZ, Wei SQ, Lian LA. Intravoxel incoherent motion MR imaging: Evaluation of myocardial microcirculation in diabetes patients In: Proc 27th Annual Meeting ISMRM, Montreal; 2019 p 0291.
10. Scott AD, Ferreira PF, Nielles-Vallespin S, et al. Optimal diffusion weighting for in vivo cardiac diffusion tensor imaging. Magn Reson Med 2015;74:420–430 [PubMed: 25154715]